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J. L. Lumley

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Beginning with the code flo103 of Jameson and Martinelli, a robust, flexible numerical platform has been constructed which can accept O and R meshes as well as C, accepts a variable number of PDEs in the turbulence models, has consistent gradient compensation, enhanced multi-grid sequencing, a restart option, various post-processing options, the option of recording convergence histories, accepts k-ε, k-ε-S, second order and Baldwin-Lomax turbulence models, has dynamical memory allocation, vectorized data structure and Unix integration, and computes subsonic, transonic and supersonic flows. Virtually any turbulence model can be run in essentially any two-dimensional geometry, so that they can be compared on an equal footing. The following cases have been computed: homogeneous grid turbulence; plane jet and mixing layer; flat plate boundary layers; semi-infinite plate (subsonic (Clauser) and supersonic (Delery)); finite plate (subsonic (ONERA)); supersonic compression ramp (Settles et al - Mach 2.93); Delery bump. Documentation is in preparation.

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Final Technical Report

F49620-92-J-0038 (Turbulence Modeling)

1 October 1991- 30 September 1994

James M. McMichael, Program Manager

Principal Investigator
John L. Lumley

AFOSR F49620-92-J-0038
TURBULENCE MODELING:
Second-Order Closures for Compressible Turbulence
in External Aerodynamics

D.A. Caughey, J.L. Lumley, S. Savarese, C.C. Volte

April 12, 1994

Abstract

An extensive bibliography was compiled in the fields of second-order turbulence closures and compressible turbulence modeling. A method for the numerical simulation of compressible turbulent flows was devised. An existing CFD code was modified to solve an arbitrary number of PDE's. Other changes included grid topology, spatial discretization, boundary conditions and programming optimization. Implemented turbulence models are: Baldwin-Lomax, ASM, k-ε, k-ε-S, second-order closures. Validation of the 2D solver is under way. The interaction between turbulent boundary-layer and shock wave was studied and its dynamical modeling is being investigated.

1 CFD Code Generation

The original code FLO103 provided by Antony Jameson and Luigi Martinelli from Princeton University featured a finite-volume centered-space discretization scheme with fourth- and second-order artificial dissipations, a multistage Runge-Kutta time integration algorithm with multigrid convergence acceleration as well as various boundary conditions. The provided turbulence models were Baldwin-Lomax and algebraic stress model. Graphics output was generated using PLOT3D.

The current code CYSTE comprises the following improvements:

- Software Engineering: in order to minimize the run-time memory requirements, a dynamical memory allocation was implemented using a C main program, driving the dependent FORTRAN 77 scientific code. Both functional and data structures were vectorized allowing for a variable number of equations to be solved. A Unix User interface (UUI) was developed to select physical models and geometries as well as to archive results. Our concern focused on the issues of reliability, maintainability, expandability and modularity. A reasonable level of these has been achieved. Computer resource optimization, geometry and boundary condition versatility are nearing completion in the two-dimensional version of CYSTE.

- Geometry: CYSTE requires structured meshes but the grid topology was extended from C- only to rectangular, O- and C- meshes.

- PDE solver: the algorithm was vectorized allowing for a variable number of equations to be solved. The finite-volume space discretization was modified to enforce a conservative computation of the gradients of the dependent variables, the laminar fluxes and the turbulence source terms consistent with that of the convective fluxes.

- Convergence Acceleration: the multigrid scheme was improved by a consistent enforcement of boundary conditions.

- Input/Output: an option enables restarting from previous results to reduce the required CPU-time to reach converged state. The convergence history is monitored for all variables. The data post-processing for graphics output has been adapted to TECPLOT.

- Turbulence models (currently under development): all k-ε, k-ε-S, Reynolds-stress closures (Isotropization

  of production (Naot et al.), Shih & Lumley) account for mean compressibilty effects only. Various simple boundary conditions have been tested. Result evaluation for validation is under way. Modeling of dynamical compressibility effects of density fluctuations follow (cf. Modeling) as well as refined wall-function approaches.

2 Modeling

2.1 Turbulence

An extensive bibliography was compiled in the fields of second-order turbulence closures and compressible turbulence modeling. A method for the numerical simulation of compressible turbulent flows was devised. The relationship between density-weighted (Favre) and classical (Reynolds) statistical averaging was carefully explored. Both finite-moment averaging procedures were carried out on the equations of motion. This led to a mixed formulation of the governing equations. The closure requirements were assessed for both formulations, including:

- solenoidal dissipation: the evolution for dissipation can be modified to account for strain-rate history by consideration of the inverse time scale S introduced by Lumley ("Some comments on turbulence", J.L.Lumley, Phys. Fluids A4 (2), Feb. 1992).

- dilatational dissipation and pressure-dilatation correlation: explicit modeling of compressibilty effects was then integrated ("Toward a constitutive relation in compressible turbulence", O.Zeman, Fluids A4 (2), Feb.1992; "Analysis and modeling of dilatational terms in compressible turbulence", S.Sarkar et al. Jour. Fluid Mech. 227, 1992)

2.2 Shock-wave

In external transonic flows, the interactions between boundary-layer, shock wave and induced separation region (when present) were studied. The oscillation of the shock waves would be explained by the bursting of vortices in the incoming turbulent boundary-layer and/or by the "breathing" of the separated region. These phenomena cannot be accounted for by the current adopted level of physical description . Thus, a dynamical model – including the average "pumping" effects of turbulence by the shock wave oscillations as well as those of separation on the oscillation amplitude – is currently under investigation.

2.3 Constitutive Laws

- Equation of state: real gas effects being negligible for non-reacting aerodynamic flows, the perfect gas law was expressed with internal energy dependent thermodynamic coefficients.

- Thermal and momentum closures: diffusion coefficients were calculated in a similar way. Fluctuations of diffusion coefficients were retained in an order of magnitude analysis of the turbulent quantities.

3 Project Outline

The purpose of the project is twofold: validate a finite-volume code with second-order turbulence model for realistic engineering design and compare performances of second-order closures to simpler turbulence models including specific modeling of the compressibility effects.

Several well-documented benchmark flows are selected to test the accuracy and performance of the computational engine. An extensive comparison of the performance of common and new turbulence models results in the characterization and validation of the models for different types of flows. Based on this classification, the relevant models are applied to more complex flow cases of industrial engineering interest. The correlation between the performance of the models in both simple and complex flows is used to evaluate the validity and versatility of the initial modeling method and physical arguments.

In order to conduct a comparative study of these models, a precision tool is needed: all models need to be implemented in a single, accurate computational engine. Variations in the details of the computational methods (accuracy, stability, convergence properties, geometry specification) jeopardize the objectivity of conclusions regarding the performances of various models. These unknowns must be eliminated in order to ensure a fair judgment.

Hence, we elected to devote a great deal of efforts and time to the design and optimization of the CYSTE numerical simulation package. CYSTE will be extended to three dimensions in spring 1994. Since the flow solver is second-order accurate in both space and time, unsteady solutions can also be generated. The study of two-dimensional flows is necessary, essentially because most numerical simulations have been two-dimensional in the past twenty years. This is not an important restrictions for many applications, but there are some inherently three-dimensional flows which require three-dimensional simulations, just as some unsteady flows cannot be accounted for by steady solutions. However, while accurate three-dimensional steady or two-dimensional unsteady solutions can be obtained at a reasonable cost, three-dimensional unsteady solutions may be very limited in space and time resolution, depending on the available computing resources.

The upgrade from 2D to 3D should be completed by June 1994. A tuning of the models in 3D will be performed on simple geometries (flat plate, jet, mixing layer) before computing the benchmark flows (M6 wing with shock-induced separation (ONERA data), backward-facing step (Stanford), wing-tip separation (ONERA)).

Thorough testing of the compressible second-order models is critical in gaining acceptance from the industrial community. This study will both rate their performance in engineering design situations and enable an accurate comparison with lower-order closures.

The study is being completed by two graduate students under the supervision of professors John Lumley (turbulence) and David Caughey (CFD).

EXECUTIVE SUMMARY

Attached are the annual technical reports for this contract, describing the research progress during each of the three contract years, and listing the publications and other data.

The final state of this work is as follows: by the second week of December 1994, the students Savarese and Volte had not completed all the various test flows computed with all the various models, although they had made substantial inroads on this project. The students' Special Committees declined to consider granting them their degrees, since the work was not completed. At that time, the students were committed to return to France to take up positions with SNECMA, which had partially financed their graduate education. They agreed to complete the work in France, as soon as they were settled in their new jobs, at no further cost to this contract, and to return to Ithaca to defend their theses when the work was completed. I am in frequent communication with them, and they are making substantial progress toward completion of this work.

Specifically, they have completed the adaptation to the local computer setup. This involved modifications of the following procedures:

Post-processing: they are now using IRIS Explorer, a complete, precise, powerful data exploration tool. 2D contour plots and 1D slices can be extracted.

Mesh generation: examination of various numerical problems in free shear flows indicated that the grids were not fine enough in high gradient regions (e.g. inlet). A new algorithm was devised to better control mesh size (spanning ten orders of magnitude is no longer a problem) and mesh clustering (cell size ratio less than 1.2 or any other bound).

Artificial dissipation: required special treatment at solid boundaries to prevent spurious oscillations on very fine meshes (improvement of the functional dependency of the artificial dissipation coefficients upon local Mach number).

Turbulence models: compressibility terms have been modified in addition to the implementation of Cyril's Mt model.

Realizability: a new clipping algorithm has been implemented (VIRUS= Variable Increment Realizability Upholding Scheme, by Stephan) enforces realizability before violations occur during the iterative process.

To date they have computed the following cases (with the indicated results):

Homogeneous Grid Turbulence: unchanged.
Plane Jet and Mixing Layer: refined meshes, improved convergence, faster recovery of the equilibrium profile.
Flat plate boundary layers
Semi-Infinite Plate: subsonic (Clauser) and supersonic (Delery).
Finite Plate: subsonic (ONERA).
Supersonic Compression Ramp: Settles et al. (Mach 2.93)
Delery bump: results should be available within a week or two of this writing.

The students plan to forward results on the simplest cases by the end of August 1995, and on the more complex cases sometime during September.

4

The students (Stephan Savarese and Cyril Volte) began with the Code flo103 of Jameson and Martinelli. This was extensively modified to accept O and R meshes as well as C meshes, to accept a variable number of PDEs in the turbulence models, to have consistent gradient compensation, enhanced multi-grid sequencing, a restart option, various post-processing options, the option of recording convergence histories, to accept k-ε, k-ε-S, and second order turbulence models in addition to the Baldwin-Lomax, and to have dynamical memory allocation, vectorized data structure and Unix integration. This was a major undertaking, and has been very time-consuming. The work is now completed, and we have what we desired: a numerical platform which can be used to run any turbulence model in nearly any two-dimensional geometry, so that they can be compared on an equal footing.

The various turbulence models, modified for transonic flows, have been installed. Generally speaking, the modifications have consisted of inclusion of appropriate forms for the dilatational dissipation, the pressure dilatation correlation, and shock-turbulence interaction. The models of Zeman, Sarkar and Yoshizawa are being evaluated. So far as shock-turbulence interaction is concerned, Dolling has suggested that the frequency of the shock oscillation is related to the frequency of vortex bursting in the incoming boundary layer, and we favor this explanation. This frequency is proportional to u_τ^2/ν. This suggests a relative simple parameterization for the shock-turbulence interaction, and we are exploring this. We are implementing the models first in their incompressible form, for homogeneous flows, flat plate boundary layers, and for jets and mixing layers. We are then proceeding to the compressible forms, and will be investigating (among other flows) a symmetrical bump in a channel to examine shock-induced separation. A two-dimensional airfoil will be our final effort. We are currently having some trouble near the boundary with the k-ε and k-ε-S models.

The current phase will be completed by the second week in December 1994. The progress at present is very rapid, now that the numerical platform is fully operational. Unfortunately, we will not have the time to investigate three-dimensional flows and more realistic geometries; the time necessary for the development of the numerical platform was considerably greater than anticipated.

PIADC

Name (Last, First, MI): Lumley, John L.   AFOSR USE ONLY
                                                        Project/Subarea
Institution   Cornell University   2304/AS

Contract/Grant No. F49620-92-J-0038   NX   NM
                                            FY   94

NUMBER OF CONTRACT/GRANT CO-INVESTIGATORS

Faculty 0 Post Doctorates 0 Graduate Students 2 Other 0

PUBLICATIONS RELATED TO AFOREMENTIONED CONTRACT/GRANT

Name of Journal, Book, etc.: Mechanics USA 1994 (Applied Mech. Rev.)

5

Title of Article: Control of bursting in boundary layer models.

Author(s): B.D. Coller, P. Holmes and J.L. Lumley

Publisher (if applicable): N/A

Volume: 47 Page(s): S139-S143 Month Published: June Year Published: 1994

Name of Journal, Book, etc.: Phys. Fluids

Title of Article: Interaction of adjacent bursts in the wall region.

Author(s): B.D. Coller, P. Holmes and J.L. Lumley

Publisher (if applicable): N/A

Volume: 6 Page(s): 954-961 Month Published: February Year Published: 1994

Name of Journal, Book, etc.: Phys. Fluids

Title of Article: Observations regarding ``Coherence and chaos in a model of a turbulent boundary layer" by X. Zhou and L. Sirovich.

Author(s): G. Berkooz, P. Holmes, J.L. Lumley, N. Aubry and E. Stone

Publisher (if applicable): N/A

Volume: 6 Page(s): 1574-1578 Month Published: April Year Published: 1994

Name of Journal, Book, etc.: Physica D

Title of Article: Controlling noisy heteroclinic cycles

Author(s): B.D. Coller, P. Holmes and J.L. Lumley

Publisher (if applicable): N/A

Volume: 72 Page(s): 135-160 Month Published: July Year Published: 1994

Name of Journal, Book, etc.: Physica D

Title of Article: Coherent structures in random media and wavelets

Author(s): G. Berkooz, J. Elezgaray and P. Holmes

Publisher (if applicable): N/A

Volume: 61 Page(s): 47-58 Month Published: November Year Published: 1993

b

Principal Investigator Annual Data Collection (PIADC) Form (FY93)

PI Name (Last, First, MI): Lumley, John L.

Institution: Cornell University

Contract/Grant No.: F49620-92-J-0038

A. Publications in Peer-reviewed Professional Journals and Refereed Book
Chapters during the reporting period

Berkooz, G., Carlson, H., Holmes, P. & Lumley, J. L. Progress in understanding the
dynamics of coherent structures in the wall layer, control and simulation. In Near-Wall
Turbulent Flows, R. M. C. So, C. G. Speziale & B. E. Launder, eds. pp. 3-21.
Amsterdam: Elsevier. 1993.

Berkooz, G., Holmes, P. & Lumley, J. L.   Low dimensional models of the wall region in
a turbulent boundary layer: new results. Physica D 58: 402-406, 1992.

Berkooz, G., Holmes, P. & Lumley, J. L. On the relation between low dimensional
models and the dynamics of coherent structures in the turbulent walllayer. Theoretical
and Computational Fluid Dynamics. 4: 361-382, 1993.

Berkooz. G., Holmes, P. & Lumley, J. L. The Proper Orthogonal Decomposition in the
Analysis of Turbulent Flows. Annual Review of Fluid Mechanics, 25: 539-575, 1993.

Panchapakesan, N. R. & Lumley, J. L. Turbulence measurements in an axisymmetric jet
of air. Part I J. Fluid Mech. 246, 197-247, 1993.

Panchapakesan, N. R. & Lumley, J. L. Turbulence measurements in an axisymmetric jet
of helium. Part II J. Fluid Mech. 197-247, 1993.

Ristorcelli, J. R. & Lumley, J. L. Instabilities, transition and turbulence in the
Czochralski crystal melt. J. Crystal Growth., 116: 447-460, 1992.

A1. Research reports in 1993 (not in print yet, under review, etc.)

Berkooz, G., Holmes, P., Aubry, N., Lumley, J. L. & Stone, E. 1994. Observations
regarding "Coherence and chaos in a model of the turbulent boundary layer"(by X. Zhou
& L. Sirovich). *Physics of Fluids*, submitted.

Shih, T.-H., Shabbir, A. & Lumley, J. L. 1994 Realizability in second moment
turbulence closures revisited. *J. Fluid Mech.* Submitted.

Poje, A. C., & Lumley, J. L. 1994. A model for large scale structures in turbulent shear
flows. *J. Fluid Mech.* Submitted.

B. Number of additional researchers working with the Principal Investigator:

Faculty (including the Principal Investigator): 1

Postdocs: 0

7

Graduate Students: 2

C. Professional honors received by the above listed contributors during their career:

Lumley, John L.: Haute Distinction Honoris Causa - Ecole Central de Lyon, 1987; Fellow, American Academy of Arts and Sciences, 1975; Member, National Academy of Engineering, 1991; Timoshenko Medal, American Society of Mechanical Engineers, 1993; AIAA Fluid and Plasmadynamics Award, 1982; APS Fluid Dynamics Prize, 1990; Fulbright Senior Lecturer, 1973-74; Guggenheim Fellow, 1973-74; Johns Hopkins Society of Scholars; Fellow, American Physical Society; Associate Fellow, American Institute of Aeronautics and Astronautics. L. S. G. Kovasznay Distinguished Lecturer, Department of Mechanical Engineering, University of Houston. April 15, 1993.

D. Outside lectures, 1993 (place/institution, invited/contributed)

Lumley, J. L. 1993. The prospects for accurate numerical simulation of air flow in and around automobiles. Société des Ingenieurs de l'Automobile, Ecole Polytechnique, Palaiseau, Paris. Wednesday, February 24, 1993. Invited.

Lumley, J. L. 1993. Interaction of adjacent bursts in the wall region. At Turbulence Symposium in Honor of Bill Reynolds 60th Birthday. Monday, March 22, 1993. Invited.

Berkooz, G., Carlson, H., Holmes, P. & Lumley, J. L. 1993. Progress in understanding the dynamics of coherent structures in the wall layer, control and simulation. International Conference on Near Wall Turbulent Flows, Tempe AZ, 15-18 March 1993. Invited.

Lumley, J. L. 1993. Turbulence: a perennial problem. L. S. G. Kovasznay Distinguished Lecture, Department of Mechanical Engineering, University of Houston. Thursday, April 15, 1993. Invited.

Lumley, J. L. , Leibovich, S., Holmes, P., & Guckenheimer, J. 1993. Structure and control of the wall region in a turbulent boundary layer. AFOSR Contractors' meeting. May 24-25, 1993. Chrysler Center, University of Michigan. Invited.

Lumley, J. L. 1993. A new model for the turbulent dissipation. Summer School / Workshop "Modeling turbulent flows", 14-25 June, 1993. Laboratoire de Mécanique des Fluides, Ecole Centrale de Lyon, France. Invited.

HONORS/AWARDS RECEIVED DURING CONTRACT/GRANT LIFETIME

Lumley, John L.: Haute Distinction Honoris Causa - Ecole Central de Lyon, 1987; Fellow, American Academy of Arts and Sciences, 1975; Member, National Academy of Engineering, 1991; Timoshenko Medal, American Society of Mechanical Engineers, 1993; AIAA Fluid and Plasmadynamics Award, 1982; APS Fluid Dynamics Prize, 1990; Fulbright Senior Lecturer, 1973-74; Guggenheim Fellow, 1973-74. Fellow, American Physical Society; Associate Fellow, American Institute of Aeronautics and Astronautics.